ENVIRONMENTAL HEALTH PERSPECTIVES

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http://dx.doi.org/10.1289/ehp.1306709

Received: 25 February 2013

Accepted: 7 May 2014

Advance Publication: 9 May 2014

Estimating the Number of Low-Income Americans Exposed to Household Air Pollution from Burning Solid Fuels

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Running title: Household Air Pollution in the US

Acknowledgments: This research has been supported, in part, by the Intramural Research Program of the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development. We thank Larry Brockman and Leigh Herrington of the Environmental Protection Agency for their review of the manuscript and help in identifying important background material.

Competing financial interests: The authors declare that they have no actual or potential competing financial interests.

Abstract

Background: Exposure to household air pollution (HAP) from inefficient biomass and coal stoves kills nearly four million people every year worldwide. HAP is an environmental risk associated with poverty that impacts an estimated three billion people mostly in low- and middle-income countries.

Objectives: To estimate the number of low-income Americans exposed to potentially health damaging concentrations of HAP.

Methods: We mapped county level data for the percentage of households using wood, coal, and/or coke as their primary heating fuel and percent of the population below the Federal Poverty Level. Using US Census data and the likelihood of fugitive emissions as reported in the literature, we estimated the number of low-income Americans potentially exposed to HAP.

Results: Solid fuel is the primary heating source for more than 2.5 million US households or 6.5 million people. The mapping exercise showed several rural areas, primarily in the north and western regions, that have high levels of solid fuel use and poverty. We then identified 117 counties with high co-incident poverty and solid fuel use as high priority counties for research into potential health risks from HAP. We estimate that between 500,000 and 600,000 low-income people in the US are likely exposed to HAP from burning solid fuels within their homes.

Conclusion: HAP occurs within the US and should be further investigated for adverse health risks, especially among those living in areas with rural poverty.

Introduction

Worldwide, three billion people rely on burning biomass and other solid fuels for cooking and heating within their homes (World Bank 2011). Each year, exposure to household air pollution (HAP) from inefficient stoves kills 3.5 million people directly, and another 0.5 million people from HAP's contribution to outdoor air pollution (Lim et al. 2012). In general, these people live in extreme poverty within low- and middle-income countries (LMIC) and procuring fuel for heating and cooking consumes much of their time and resources (World Bank 2011). HAP is an independent risk factor for low birth weight, childhood pneumonia, chronic obstructive pulmonary disease (COPD), cataracts, cardiovascular disease and lung cancer (Boy et al. 2002; Kurmi et al. 2010; Lee et al. 2012; McCracken et al. 2011; Pope et al. 2010; Smith et al. 2000; World Health Organization 2009; Zhang and Smith 2007; Zhong et al. 2007). Other outcomes have been proposed, but the evidence is less definitive for asthma, cancers other than lung, pneumonia in adults, and infectious diseases such as tuberculosis or HIV (Fullerton et al. 2008; Smith et al. 2004). Awareness of these health risks has sparked a global effort to have 100 million households adopt clean cooking technologies by 2020 (Martin II et al. 2011; United Nations Foundation 2012).

The problem of HAP is less often studied in developed countries. However, a growing body of literature suggests that despite the relative affluence of developed countries, the rural poor in the US, and perhaps elsewhere, are at risk due to HAP exposure in much the same way as occurs globally (Barry et al. 2010; Bulkow et al. 2012; Bunnell et al. 2010; Johnston et al. 2013; Noonan et al. 2012b). HAP most often results from the daily inefficient combustion of fuels indoors without sufficient ventilation to remove emissions (Lim et al. 2012; World Bank 2011). The same principle holds for HAP in developed countries where "fugitive emissions," products of incomplete combustion which escape the stove or flue, pollute the indoor environment. However, important differences exist between HAP globally and within the US (Naeher et al. 2007). Namely, very few stoves within the US function without a flue and most stoves are used for heating seasonally as opposed to year round cooking. Also, the duration that children are exposed to HAP is likely less in the US where children are most often in school for a significant portion of the day, during the heating season. While these differences change the type and duration of exposure, significant health risks may remain. Globally, HAP is tightly linked with poverty as families have limited financial resources to spend on more efficient stoves or fuels (World Bank 2011). In this study, we sought to determine areas of the US where poverty and household solid fuel use co-exist, and to provide an estimate of the number of low income Americans at risk from fugitive emissions escaping from the indoor stoves. In order to quantify the potential scope of the problem, we utilized publicly available data sets to estimate the number of households in the US with coincident primary solid fuel use and low income. We then used the literature to estimate the likelihood of fugitive emissions in such households and calculated the number of people living in poverty in America who could be at risk for poor health from HAP.

Methods

To determine the number of households that utilize solid fuels as their primary heating source and live below the Federal Poverty Level (FPL) in the US, we queried the US Census Public Use Microdata Sample (PUMS) for the American Community Survey (ACS) 5-year estimate 2006-2010 (US Census Bureau 2012). The PUMS of the ACS provides a national and state-wide estimate of households that use solid fuels as a primary heat source. The FPL is defined by using set income levels adjusted for inflation and family size; for example, the FPL in 2011 for a family of four with two children was $22,811 (US Census Bureau 2012). Data on poverty and the rural-urban continuum score (year 2004) came from the Economic Research Service of the US Department of Agriculture (USDA) (US Department of Agriculture 2012). We combined these data using the Federal Information Processing Standards (National Institute of Standards and Technology 2012) codes and imported the data into the mapping software Health Landscape (Health Landscape 2012). Using the mapping software, the county level data were then displayed using a geographic boundary file for 3,144 counties and county equivalents in the US in 2010. The county level rates for solid fuel use and poverty were assigned to nine equal quantiles and color coded using Health Landscapes, which allows information that has been geocoded by coordinates or to state, county, or local boundaries to be displayed on preset maps.

To identify priority counties potentially at risk from HAP, we compiled a list of counties with high co-incident primary solid fuel use and percent of households below the FPL. We defined counties as high priority where 10% or more of the households use solid fuels as their primary heating source and where 20% or more of the households have incomes below the FPL (Supplemental Material, Table S1 and Figure S1).

To develop an estimate of the risk for HAP from fugitive emissions released from household stoves in the US, we searched the scientific literature from 1990 to 2013 for studies of US households using solid fuels with the following search terms: household air pollution, indoor air pollution, air pollution, poverty, wood stove, and coal stove. The search revealed only a few studies that documented indoor air quality in US-based homes using solid fuels as a primary heating source (Bunnell et al. 2010; Noonan et al. 2012a; Paulin et al. 2013; Robin et al. 1996; Ward et al. 2011; Ward et al. 2008). For each study, we attempted to determine the percentage of homes whose 24-hour average for $PM_{2.5}$ exceeded the World Health Organization (WHO) recommended level of 25 µg/m^3 (World Health Organization 2005). We chose the WHO guideline for $PM_{2.5,}$ as the WHO standard is used for both indoor and outdoor air pollutant levels, as opposed to the daily EPA National Ambient Air Quality Standard of 35 µg/m^3 used for ambient air pollution alone (Environmental Protection Agency 2014). Of these, only three studies provided sufficient data to develop an estimate of the percentage of homes with $PM_{2.5}$ levels that exceed the WHO 24-hr standard (Bunnell et al. 2010; Noonan et al. 2012a; Ward et al. 2011). Bunnell et al. was conducted near Shiprock, New Mexico on the Navajo Nation, and 19 homes were surveyed (2010). Noonan et al. was conducted in Libby, Montana, and 26 homes were surveyed (2012a). Ward et al. 2011 was conducted on a Nez Perce reservation in Idaho with 16 homes (2011). The studies were conducted in geographic areas or populations with more than 20% of the households below the FPL, one of the criteria for the "high priority" counties in the Supplemental Material (US Census Bureau 2012).

However, two factors may potentially confound the interpretation of the high indoor $PM_{2.5}$ levels due to contributions from other sources such as: 1) indoor tobacco smoke and 2) ambient air pollution. The studies by Ward et al. and Noonan et al. excluded homes with self-reported smokers, and Bunnell et al. tracked whether cigarette smoking occurred during a study period and no smoking was reported during the winter heating season. These steps minimize or eliminate the possible confounding influence of environmental tobacco smoke (ETS). Regarding the indoor contributions from ambient air pollution, the two studies that changed-out stoves and repeated $PM_{2.5}$ levels found that the reductions in indoor $PM_{2.5}$ were not associated with changes in ambient levels (Noonan et al. 2012a; Ward et al. 2011). Additionally, the studies that measured ambient $PM_{2.5}$ levels found that indoor concentrations were much higher than outdoor concentrations during sampling periods, suggesting that contributions from ambient pollution to indoor air pollution were likely small. While excluding homes with ETS allows for a more specific estimate of the health and other impacts of burning solid fuels, it may well underestimate the number of households with indoor air quality above the WHO standards in our analysis as burning solid fuels and tobacco use likely overlap in many households (Paulin et al. 2013). Thus, the three studies selected to estimate the number of households at potential risk from fugitive emissions are the best currently available and address the impact of tobacco smoke and ambient pollution in a consistent and logical manner.

Results

The mapping exercise in our study reveals that solid fuel use appears concentrated in the northern and western regions of the US with some pockets of high use in the Midwest and Appalachian regions (Figure 1). In the US, household solid fuel use is predominantly for heating, and the mapping of the US Census data reflects areas of more temperate climate with seasonal needs for heating. There are many areas of poverty that consistently overlap with areas of solid fuel use (Figure 1A), although high poverty tends to be concentrated in the south where use of solid fuels for heating is much lower (Figure 1B). Most notably, areas of solid fuels use and poverty co-exist in Southwest and Central Alaska, the Four Corners region of New Mexico, Arizona, Utah, and Colorado, Appalachia particularly parts of Kentucky and West Virginia, and pockets throughout the Pacific Northwest. We identified 117 counties meeting the criteria for high co-incident primary solid fuel use and percent of households below the FPL (Supplemental Material, Table S1, Figure S1). Of these 117 counties 107 are considered rural by the USDA rural-urban continuum score (US Department of Agriculture 2012). As many as 600,000 people could be at risk for ill health due to high level HAP exposure in the US (Table 1). We calculated the number of people exposed to risk from HAP by multiplying the number of people who live in poverty and use solid fuel as their primary heating source (900,000) by the range of values for the percentage of homes experiencing 24 hour average $PM_{2.5}$ concentrations exceeding the WHO recommended level of 25 μg/m^3 (between 53-65% as shown in Table 1) (2005). Air pollution above 25 μg/m^3 has been shown to negatively impact human health (World Health Organization 2005). In this calculation, we assumed that the measurements of HAP were taken within homes representative of homes below the FPL. Unfortunately household income was not specifically reported in any of the three studies used to establish the % of homes exceeding the WHO indoor standard (Bunnell et al. 2010; Noonan et al. 2012a; Ward et al. 2011). However, US Census data reveal that each of the studies was conducted in a geographic areas or populations where 20% or greater of the population lives below the FPL (Navajo Reservation-38%; Libby, Montana-22%; Nez Perce Reservation-15% for all residents and 22% among Native Americans, the study population) (Bunnell et al. 2010; Noonan et al. 2012a; Ward et al. 2011; US Census Bureau 2012).

Discussion

The burning solid fuels for heating occurs seasonally in large regions of the US, and HAP can be found in rural areas with a history of poverty (Barry et al. 2010; Bulkow et al. 2012; Bunnell et al. 2010; Noonan et al. 2012b; Ward et al. 2011). In this study, we present a geographic distribution of household solid fuel use, and an estimate of the number of low-income Americans at risk from exposure to HAP. Based on the available evidence, we estimated that between 500,000 and 600,000 low-income Americans are at risk for adverse health effects as a result of HAP. To our knowledge, this is the first paper to estimate of the number of low-income Americans potentially exposed to HAP from household solid fuel use, using the US Census and extrapolating the number of households at risk from HAP based on the existing scientific literature. While these studies employed non-random sampling, were small in size, and did not record demographic information such as household size or income, they are the best available evidence (Bunnell et al. 2010; Noonan et al. 2012a; Ward et al. 2011; Ward et al. 2008). Without specific household income information, it is not possible to verify whether all of the homes included in these studies were indeed representative of households with incomes below the FPL. The nonrandom selection of households for monitoring may tend to overestimate the likelihood of fugitive emissions to the extent that study participation may be biased to households with higher emissions. However, our estimate of Americans at risk from household solid fuel use is likely conservative. We did not estimate the total exposure from solid fuel use by including the contribution of vented emissions to ambient air pollution, as was done for household air pollution in the global comparative risk assessment report (Lim et al. 2012). Furthermore, we did not attempt to include the approximately 9 million households that use solid fuels as a secondary source of heating as peer-reviewed data currently do not exist on the level of fugitive emissions from stoves and fireplaces amongst secondary users (US Energy Information Agency 2012). The selection of the WHO 24-hour average recommendation for $PM_{2.5}$ may also have resulted in an underestimate of those at risk because the WHO has recommended an annual average of 10 $\mu g/m^3$ for $PM_{2.5}$ and if measurements in the sampled homes are indicative of standard practices then more homes might have exceeded this lower standard. However, each of the studies upon which this analysis relied reported their findings as 24-hour average $PM_{2.5}$. Ideally, future estimates of adverse health risks should be based on direct measurements as part of a coordinated set of regional stove changeout programs with enough households to achieve sufficient statistical power to more accurately extrapolate the burden of disease risk nationally.

The priority counties that we identified were predominately rural, 107 out of 117, according to the USDA county typology codes (US Department of Agriculture 2012). These counties, on average, also have higher infant mortality, and their average death rate from chronic lower respiratory disease was nearly twice the national average (Health Indicators Warehouse 2013). While the association with poor health outcomes is purely ecological, as it cannot be verified whether homes with high solid fuel use also have a higher burden of disease, studies linking HAP and markers of respiratory health have been conducted in several of counties we identified (Barry et al. 2010; Bulkow 2012; Morris et al. 1990; Noonan et al. 2012b; Robin et al. 1996). This strengthens our confidence that despite the risk for ecologic fallacy inherent in such comparisons, there may be an association between HAP and ill health in these counties. Future research on HAP and changeout programs should focus on these priority counties or counties with similar characteristics in order to be most effective.

There are differences with HAP in the US compared with HAP in LMIC (Naeher et al. 2007). First, heating in the US is usually a seasonal need and thus one might expect overall exposures from solid fuel use to be less when compared to those in LMIC where the predominant daily energy need is for cooking. Second, solid fuel use in the US also occurs among non low-income families as an optional and supplemental source of fuel for heating or simply for recreational use in the home; additionally some non low-income families may choose it as their primary heating fuel for additional real or perceived benefits (carbon neutrality, cost stability, etc.) (Allen et al. 2009; Naeher et al. 2007). However, even in non low-income homes with seasonal wood fuel use, the levels may not be entirely safe, though the studies remain to be done to provide accurate estimates. There is ample evidence that woodsmoke contributes significantly to ill health in airsheds surrounding such cities as Seattle (Naeher et al. 2007). This demonstrates the large “neighborhood” effect of inefficient woodstoves and suggests that the unsafe use of indoor solid fuels for heating is not limited to households in poverty. Despite these differences, there are similarities between the solid fuel use in US and LMIC. For example, like LMIC solid fuels may be the only fuel source available in populations with a lower SES. For those living in a rural US community with a lower SES, the release of fugitive emissions into the households may occur more often due to the increased financial burden associated with purchase of more efficient heating stoves or the routine maintenance/inspection necessary to assure adequate ventilation of emissions. As is the case globally, the individuals and families who bear the greatest risk are also the ones who can least afford to make health-promoting changes to counteract these risks. HAP is an environmental justice issue both domestically and globally. Various types of solid fuels may be used in households in the US and globally, some of which have different impacts on health outcomes. For example, household use of coal which remains common in China is associated with a higher risk of lung cancer than wood fuel use alone (Straif et al. 2006). While the majority of people in the US who use solid fuels as their primary heating source use wood (6.1 out of 6.5 million), the remainder who use coal and coke (US Census Bureau 2012) may be more likely to have health effects similar to those elsewhere in the world who use coal as their primary household energy source.

Health risks from household solid fuel use are not limited to household exposures. In rural areas, communities with a high proportion of household solid fuel use with emissions vented outside may significantly contribute to ambient air pollution and place entire communities and regions at risk for adverse health outcomes (Johnston et al. 2013; Larson et al. 2004; Noonan et al. 2012b; Sheppard et al. 1999; Ward and Lange 2010). In fact, the Libby, Montana woodstove changeout program reduced average winter ambient $PM_{2.5}$ by 28%; and, in the small subset of homes in which household monitoring occurred, 24-hour average household $PM_{2.5}$ was also reduced by 53% (Noonan et al. 2012a; Noonan et al. 2012b). These improvements in air quality were associated with reductions in respiratory symptoms in children including parent-reported respiratory infections (Noonan et al. 2012b). Thus, adverse health effects result not only from the direct exposure to HAP, but also from its contribution to ambient pollution in the wider community. These findings are also consistent with the recent report by Lim et al. (2012) noting that almost 0.5 million additional deaths from HAP occur each year globally as a result of the impact of HAP on outdoor air pollution.

Especially when HAP is viewed in the context of poverty, there are confounding factors that can also adversely impact health including higher risk for infections, poor nutrition, and other environmental health risks. Smoking and ETS within the home also represent a significant challenge in studying the health effects of HAP (Noonan and Ward 2007; Paulin et al. 2013). However, the effect of HAP can often still be found, even in the context of confounders. For example, in Alaska Native villages where smoking rates among women are as high as 60% (Kim et al. 2010), having a wood or coal stove in the house was a significant independent risk factor for acute lower respiratory tract infection in children under three years of age (Bulkow et al. 2012). As with all research on environmental exposures it is difficult to separate the effects of multiple exposures. Future studies should seek to determine the effects of HAP through careful exposure monitoring. Examples of such studies include the recently announced randomized controlled trial in the US using asthma as an outcome, that is beginning to publish results, and a randomized trial using air filtration and measuring endothelia function in a woodsmoke impacted community (Allen et al. 2011; McNamara et al. 2013; Noonan and Ward 2012).

The 500,000 to 600,000 low-income individuals potentially at risk from HAP in the US merit the attention of the scientific and policy-making communities. The number of people affected by HAP in the US may be modest in comparison to other sources such as traffic related air pollution (Health Effects Institute 2010). This does not negate the fact that those affected by HAP tend to have high exposures for months at a time and as occurs with HAP elsewhere in the world, often have limited options to reduce the exposures. To enhance the accuracy of this estimate, additional studies are needed with detailed indoor and outdoor exposure monitoring of households and communities that commonly use solid fuels for heating, so that reductions in exposure can be verified and correlated with health outcomes. Such work will provide the necessary data to elucidate the health effects across the life cycle and better account for differences in disease severity and societal cost based on the specific subpopulations most affected. Future studies may provide impetus for public policy changes to foster improved air quality and hopefully improvements in health of underserved and vulnerable populations in the rural US. Potential health risks exist from household burning of solid fuels in wealthier countries, particularly in poor areas where households may lack access to clean burning technologies. Investments by developed countries such as the US to help solve these environmental risks in LMIC, where 40% of the world's population lives with far greater household exposures, may also prove valuable to address solid fuel use in high poverty areas at home.

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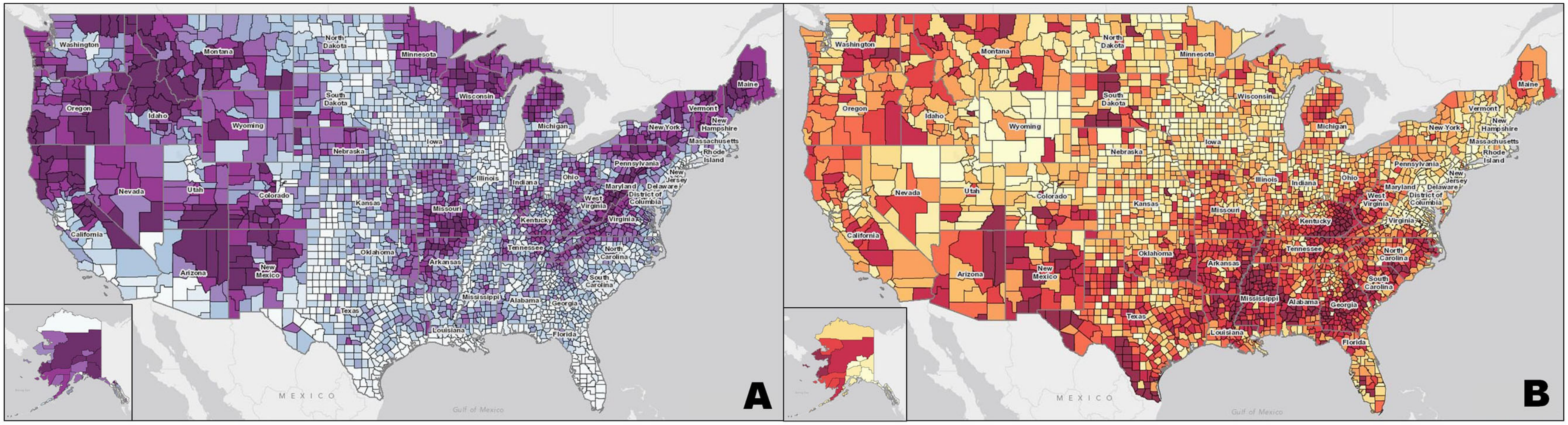
Table 1. Estimate of the number of people at risk for ill health from HAP due to burning solid fuels in the US.

Number	Source
Approximately 6.5 million people in the US live in homes heated primarily by wood, coal, or coke.	US Census ACS 2006-2010, PUMS (US Census Bureau 2012)
Of these about 900,000 live below the FPL	US Census ACS 2006-2010, PUMS (US Census Bureau 2012)
Indoor air quality studies have shown that between 53% and 65% of homes in poorer areas that heat primarily with wood, coal or coke exceed the WHO 24-hour particulate matter guidelines (2005).	53%-Ward et al. 2011, Nez Perce Reservation, Idaho (number of homes=16); 58%-Bunnell et al. 2010, Navajo Nation (number of homes=19); 65%-Noonan et al. 2012a, Libby, Montana (number of homes-26)
Generalizing the range of 53% to 65% to 900,000 is roughly 500,000 to 600,000 people living in homes that exceed the WHO 24-hour particulate matter guidelines (2005)	Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide-Global Update 2005. WHO
Conclusion: Between 500,000 and 600,000 low-income people in the US are exposed HAP from burning solid fuels for residential heating.	

Figure legend

Figure 1. A: Map of solid fuel use by county in the US. Percent of occupied housing units utilizing either wood, coal, or coke as the primary heating fuel. Range 0-59 (white to dark purple) in 9 quantiles. Source: ACS 5 Year Estimate 2006-2010 (US Census Bureau 2012). B: Percentage of people below the Federal Poverty Level in 9 equal quantiles. Source: ACS 5 Year Estimate 2006-2010 (US Census Bureau 2012).

Figure 1.



A: Percent of the population using wood, coal, or coke as their primary heating fuel (%). 0-1 1-1 1-2 2-3 3-4 4-6 6-9 9-16 16-59

B: Percent Below the Federal Poverty Level (%). 0-9 9-11 11-12 12-14 14-16 16-17 17-20 20-23 23-53